THE ROLE OF STRUCTURAL FABRICS IN A SUSTAINABLE CONCRETE INFRASTRUCTURE

Ibell T.J.[a], Darby A.P.[b], Orr J.J.[b] and Evernden M.[b]

[a]Corresponding author, BRE Centre for Innovative Construction Materials, University of Bath, Bath, BA2 7AY, United Kingdom, t.j.ibell@bath.ac.uk, Tel +44 1225 386365, Fax +44 1225 386691
[b]BRE Centre for Innovative Construction Materials, University of Bath, Bath, BA2 7AY, United Kingdom, a.p.darby@bath.ac.uk, j.j.orr@bath.ac.uk, m.evernden@bath.ac.uk

Abstract
Concrete is the second-most used substance on Earth after water, and the production of cement accounts for at least 5% of the planet's carbon emissions. Concrete has all sorts of excellent properties, which should not be overlooked, but it seems clear that we should be exploiting these fine properties against a backdrop of needing to look carefully at how we manage our concrete infrastructure sustainably. We need to use realistic approaches to understand structural integrity of our existing concrete infrastructure if we are not to needlessly condemn adequate structures. We need to understand how to prolong the life of existing concrete structures in a robust, proven and cost-effective manner, again so that additional carbon- and energy-related costs associated with rebuild are avoided. And we need to design our future concrete structures with the most important property of concrete at the forefront, namely its moudability, something which is seldom exploited, such that efficient use of concrete is ensured. This paper outlines research conducted in the BRE Centre for Innovative Construction Materials at the University of Bath in these areas of structural strengthening and future innovative design of concrete structures. The paper focuses on the role that structural fabric can play in contributing to these aims.

Keywords: *Concrete, fibre-reinforced polymer (FRP), fabric, formwork, strengthening*

1. Introduction

The use of concrete creates a profound carbon footprint across the planet. What this ultimately means is that if we already have concrete structures in place, we should do our utmost to ensure that we prolong their lives such that we do not need to rebuild such structures. This is a key requirement. If we then wish to add to our existing building stock using concrete, we should use concrete appropriately and in an efficient manner. This paper addresses both these strands of life extension and innovative concrete structures through presenting research which the authors have conducted recently using fabric to strengthen and form concrete structures.

2. Strengthening concrete structures

2.1 The use of fibre-reinforced polymer (FRP) materials

The technique of strengthening existing concrete structures using fibre-reinforced polymer (FRP) materials is mainstream and well documented. Various design guides around the world exist to advice on such strengthening, including the UK's TR55 [1], which was lead-authored by the University of Bath. The basic idea is that one uses FRP material (usually carbon) in the form of fabric, bar, plate or strip to increase the flexural, shear or axial capacity of concrete structures by adhering the FRP to the surface of the concrete, thereby significantly increasing effective reinforcement, either directly in tension or indirectly in the form of confinement. The FRP is extraordinarily strong, stiff, durable and easy to apply. It is expensive, but where time of retrofit is paramount to project costs, the use of FRP is prolific across the world to extend the lifetime of our concrete infrastructure.

But this material does not come without drawbacks. FRP is prone to debonding from the surface of concrete before it reaches its full rupture capacity. It is also very brittle, such that ensuring that the structure still behaves in a ductile manner after strengthening is a crucial design skill, and an area which the University of Bath has researched significantly over many years. There are still question marks over fire, although the concept of fire engineering has largely solved this issue.

But the largest present drawback concerning FRP for strengthening applications is its short history. Thus, we are not yet sure about various important design considerations, because the oldest strengthening projects do not date back further than 30 years, and most are significantly more recent than that. Most strengthening schemes in buildings require that the columns are upgraded for higher axial capacity (and to be more ductile) and that the beams are upgraded for higher flexural capacity. As the flexural capacity of such beams increases, however, so too does the demand on shear capacity. Enhancing shear capacity using fabric is altogether a more difficult thing to do because of brittleness and construction issues. At Bath, we have attempted to focus our efforts on consideration of axial-strength enhancement when strengthening rectangular columns and on the problems associated with size effect when strengthening large structures in shear. Findings from these areas of research aimed at using fabric to strengthen concrete structures are discussed below.

2.2 Rectangular wrapped columns

When circular concrete columns are wrapped using FRP material, there are many potential beneficial effects on strengthening. Flexural tensile strength, shear resistance and axial capacity may all be increased. Further and probably most significant of all, the strain capacity of the concrete is increased due to excellent confining behaviour, leading to improved ductility and increased flexural strength. While square and rectangular columns also benefit from FRP wrapping, the confinement effect is less pronounced than in the circular case, due to the lack of convex curvature along the straight edges of the section. This means that the corners of the section are well confined, but not the entire cross section [2].

Recent tests have shown that the degree of confinement which rectangular columns experience when wrapped is indeed well defined in the new TR55 document, which itself is based on the model suggested by Teng *et al.* [3]. This model suggests the use of a cruciform zone of confinement, although the precise details of this have been modified for the TR55 document.

A major funded research project has just been completed at Bath. Wrapped rectangular columns of realistic size (up to 750mm in side dimension) were tested under various axial and flexural loadings in order to verify the authors' proposed design guidelines for such wrapping in TR55. Figure 1 shows the sorts of specimen which were tested using the BRE facilities. In a nutshell, this research has confirmed that the relatively high level of confinement achievable in wrapped rectangular columns under axial loading only should not be assumed for equivalent columns when also being bent. Importantly, it also appears from the results that we can indeed extrapolate smaller-scale test data for such wrapped columns. This is potentially extremely important, given the vast expense of testing at full scale.

Figure 1: *Large-scale FRP-wrapped column testing*

2.3 Size effect on shear strengthening

The use of FRP sheet fabric to strengthen concrete beams, columns and walls in shear is a well-documented technique, and the effectiveness of this system has been tested on many laboratory specimens over several years. However, up until recently, there had been no test conducted anywhere in the world on specimens greater than 600mm deep [4].

This is a major issue. If the FRP sheet is fully wrapped (typical for a column) or U-wrapped and mechanically anchored (just below the flange of a T-beam, for instance), then any shear cracking will lead to local debonding of the FRP. Such debonding will extend the full depth of the FRP, and it will strain between anchored locations as the shear discontinuity widens. If the beam is shallow, as in most laboratory tests, this strain will be substantial for a modest width of shear crack. However, if the beam is deeper (as is usually the case in reality), then the strain in the FRP will be low for a modest crack width. As the crack width increases, so the concrete contribution will reduce due to a reduction in aggregate interlock, so that the shear resistance will drop, even though the strain in the FRP is rising. The authors knew that this issue had to be serious, and went ahead with large-scale testing. Figure 2 shows one such specimen prior to being loaded in shear. It was 750mm deep. A significant size effect was indeed picked up in the testing [5].

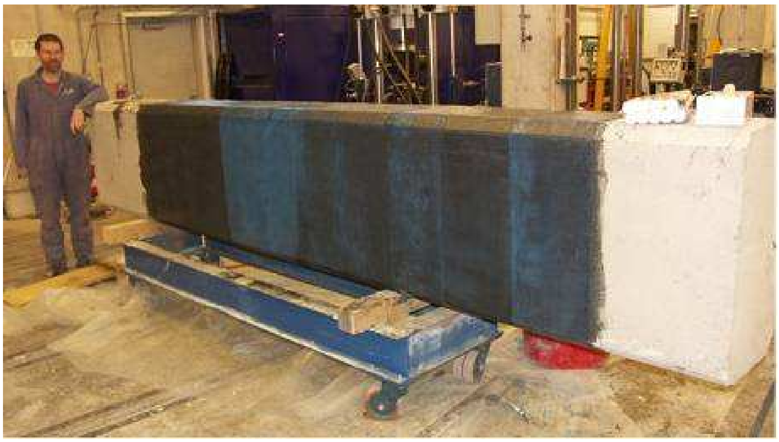

Figure 2: *Fabric-wrapped shear specimen of realistic size*

3. Fabric-formed concrete structures

3.1 Introduction

The use of fabric formwork for concrete structures can be traced back to the early 1900s, and the methods involved mainly stem from work in offshore and geotechnical engineering. In 1922 it was proposed to use concrete filled fabric bags in the construction of underwater concrete structures but it was not until the late 1960s that any real headway was made in this field, precipitated by the new availability of low cost, high strength, durable synthetic fibres that allowed the forming of complex shapes [6]. Initial interest in the architectural possibilities of fabric formwork can be attributed to the Spanish architect Miguel Fisac, who in 1969 completed the Centro de Rehabilitación para la Mutualidad del Papel (MUPAG) in Madrid. It was here that the first patented method for pre-fabricated fabric formed wall panels was developed. Subsequent developments have occurred simultaneously, yet independently, of each other. Whilst both Kenzo Unno and Rick Fearn have developed successful systems and techniques for fabric formed structures, the most influential work has come from Mark West, founder of the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba in Canada, which is the first research centre dedicated to the development and promulgation of fabric formwork for concrete structures. It is this architecturally-led work that has formed the basis for previous research at the University of Bath. This section of the paper begins by considering the principles behind fabric formwork, before focusing on the current state of the art in design, optimisation and construction of fabric formed beams.

3.2 Traditional practice

Concrete has been primarily cast in orthogonal timber or steel moulds since the mid-1800s, resulting in the well established formwork practices that exist today. Rigid formwork systems tend to be simple to construct, but consume more material than an equivalent variable section member, increasing both cost and structural dead weight. Variable section members can feasibly be produced on an industrial scale, but their geometry remains governed by primarily prismatic forms.

3.3 Fabric formwork

Forming concrete in a flexible membrane (typically a high strength polyester fabric) provides a simple method for the construction of efficient, optimised and aesthetically pleasing concrete structures that offer several advantages for engineers. The material required for a fabric formed structure is lightweight, cheap and ubiquitous – 12m span beams have been formed using under 10kg of fabric [7]. Pouring concrete into a permeable fabric results in a filtering effect in which air and water are allowed to bleed from the structure, the effect of which is twofold. First, small increases in concrete compressive strength occur that are attributable to the reduction in water:cement ratio. More significant are the increases in surface density that occur as a result of there being very few air bubbles trapped between the formwork and concrete. Increases in surface density prevent in-service moisture and air ingress into the section, thereby slowing corrosion processes and potentially allowing for a reduction in cover to steel in fabric formed structures when compared to their conventional counterparts. The distance to which this 'case hardening' effect extends into the member is unclear at present.

Fabric formwork can be stitched into almost any configuration and the boundary conditions, including support locations and degree of pretensioning, can be altered to achieve the desired form. The construction of façade panels, columns, trusses, shells and beams has already been achieved, as illustrated in Figure 3.

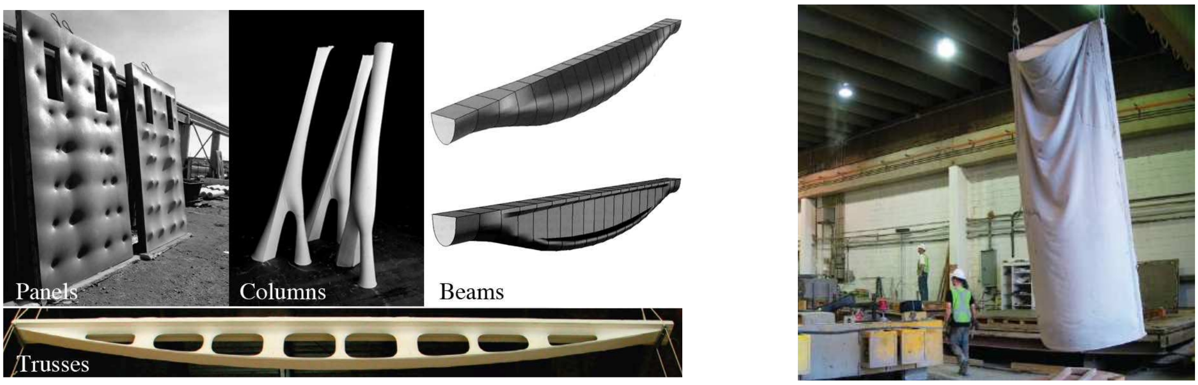

Figure 3: *Fabric formed structures (after West [7}; Garbett [8])*

3.4 Design

Design methods for fabric-formed beams are currently in a state of flux. Work at CAST has previously taken an empirical approach, and many beams were not reinforced or tested structurally. The final shape of such a beam is determined by the material properties of the fabric and boundary conditions imposed during construction.

The hydrostatic shape obtained from a given set of these boundary conditions can be accurately predicted using elastic theory, although dynamic relaxation has also been used to model the interaction between fabric and concrete [9]. In addition, Bailiss [10] and Garbett [8] used an empirical method to determine the area, perimeter and shape of fabric structures that was moderately successful. The design of fabric structures has, up to now, been approached primarily from an architectural perspective. Structural verification is now required, and this has been the focus of work at the University of Bath. Garbett implemented a sectional analysis method, as outlined in Figure 4, to design singly reinforced beams that were unreinforced in shear.

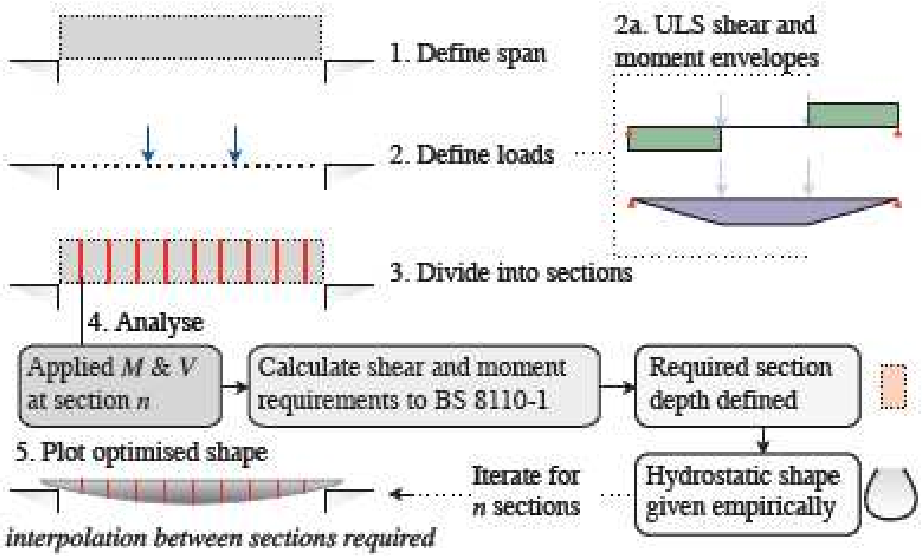

Figure 4: *Sectional design method*

Whilst the flexural strength of a reinforced concrete member can accurately be predicted using the plane section hypothesis, which forms the basis of many concrete design codes, shear design is widely considered to be an unresolved area of concrete technology. The complex cross sections of fabric formed beams make conventional shear links difficult to detail, yet omitting shear reinforcement relies on an accurate prediction of the unreinforced section's shear capacity. In many design codes around the world, the unreinforced capacity is predicted using empirical relationships based on many hundreds of beam tests, none of which were carried out on variable sections, thereby making the accuracy of these codes questionable. However, the use of the modified compression field theory in the Canadian CAN/CSA S6 [11] make this code better suited to the design of variable section members.

Longitudinal reinforcement in fabric formed beams has previously been limited to single or bundled bars, pre-bent to the desired profile. The accurate placement, and provision, of anchorage to such bars has proven to be difficult [8]. The welded end plate (Figure 5) is the most common anchorage connection, yet this leaves longitudinal steel susceptible to corrosion. The use of advanced composite reinforcement and post-tensioning offers a potential solution to this, as discussed later.

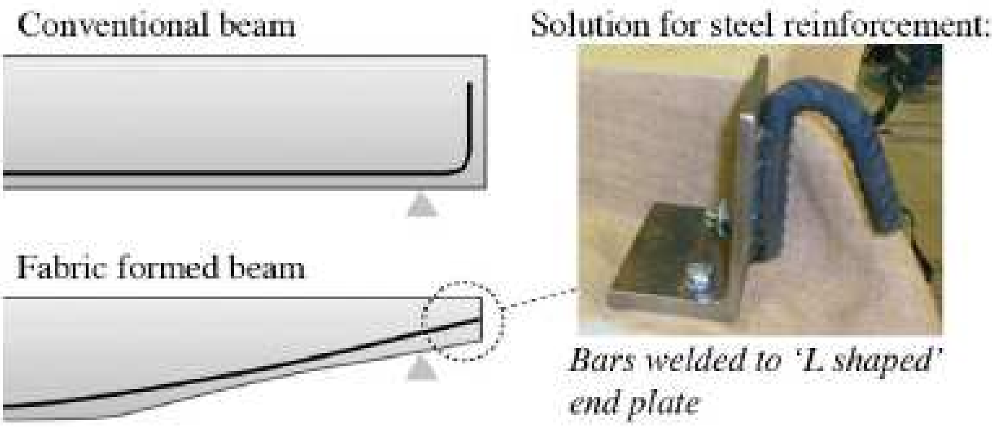

Figure 5: *Present unsatisfactory anchorage connection*

3.5 Optimisation

Optimisation can be considered as the process by which variables are used to determine the best option for a given set of parameters. Physical modelling techniques used in the past have now been all but replaced with numerical simulation methods such as evolutionary structural optimisation, solid isotropic material penalisation and sensitivity analysis that are described in detail elsewhere [12]. Structural and material optimisation is a key component of fabric formwork. Up to now, bending moment-shaped beams (Figure 3) have been optimised using the previously described sectional analysis method and material reductions of up to 50% have been obtained when compared to an equivalent rectangular beam.

This is remarkable given the simplicity of both the design and construction of these beams and offers a real opportunity for material use reductions in entire building systems. More complex approaches utilising evolutionary optimisation are currently being considered that offer two opportunities to further reduce material usage. First, through more accurate modelling of the hydrostatic shape and concrete-fabric interaction during pouring and second through improved analysis of the reinforced concrete section under loading to ensure that material is provided only where it is required. However, computational methods must always consider construction processes to ensure the optimised beam design can feasibly be built using fabric formwork.

3.6 Construction

Construction methods for fabric formed beams are continually improving. This section details four methods for the construction of variable section beams, three of which were developed by researchers at CAST [9]. The spline method (Figure 6) uses a metal bar to vertically pretension a single rectangular sheet of fabric held on a timber forming table. Pretensioning the fabric reduces the volume of concrete in the tension zone, thus providing an optimised design. Beams constructed using this method have previously had a parabolic elevation, although the final layout is determined by varying the locations and magnitude of the applied pretension. The keel mould (Figure 7) uses two sheets of fabric, held vertically and secured between sheets of plywood (the keel) that are cut to the desired beam elevation. The fabric is then draped over a forming table and pretensioned to both obtain the desired shape and to prevent wrinkling during construction.

The pinch mould (Figure 8) is used to create beams and trusses by sandwiching two sheets of fabric between a rigid timber mould. At designated locations protrusions from the timber mould ‘pinch’ the fabric to create openings in the web of the beam. The method allows the rapid construction of optimised beam elements, but constructing the formwork is more labour and material intensive than other methods. In addition, the structural behaviour of these beams is governed by Vierendeel action, which somewhat complicates their analysis. The fourth method, developed by Bailiss and Garbett utilises solely the wet concrete weight to form the beam. By predicting the shape of the fluid filled fabric, fixing points along its perimeter are determined. The fabric is then hung between two supports before being filled with concrete to obtain the desired forms, some of which are illustrated in Figure 3.

3.7 Structural tests

A total of six singly reinforced beams, designed as described in Section 3.4, have been tested in five points bending at the University of Bath [13]. Of these, five were found to fail in shear close to the supports, although two tests failed to reach their design load due to incorrect positioning of the longitudinal reinforcement. Fabrication of the beams was generally successful, and empirical methods were employed to predict the hydrostatic section shape. In general, elastic and plastic methods for the prediction of failure loads were accurate as was the prediction of load-deflection responses by double integration of curvatures along the length of each beam.

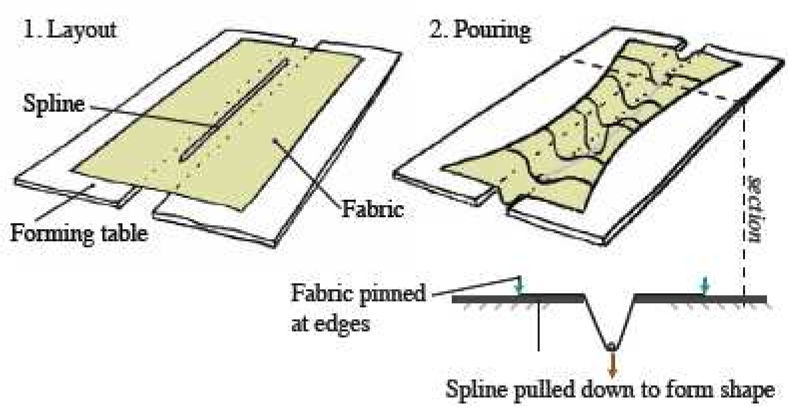

Figure 6: *Spline method*

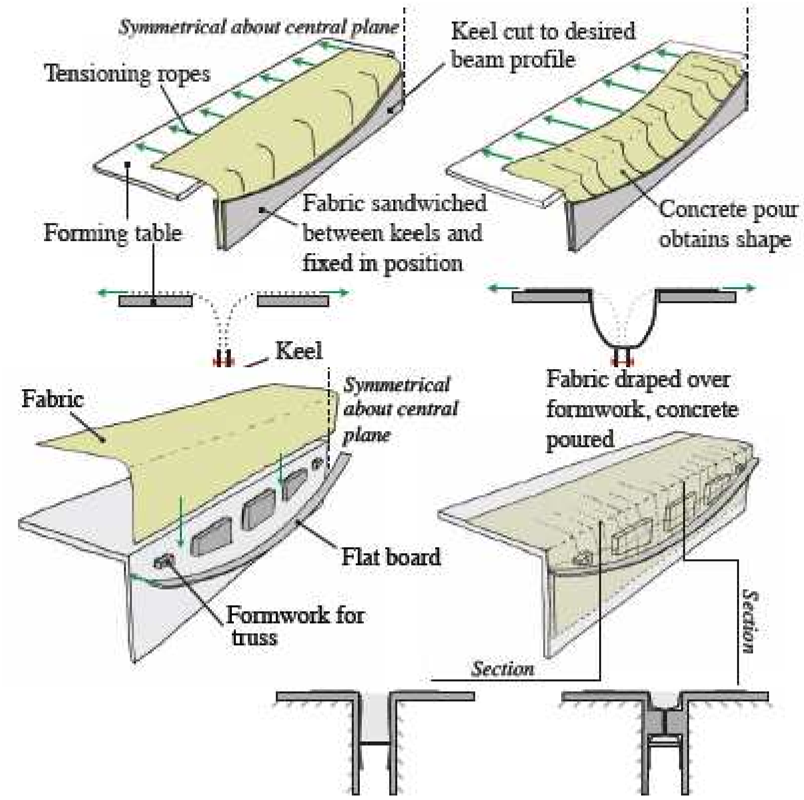

Figure 8: *Pinch mould*

The testing highlighted two areas that require further work. The predominance of shear failures in bending moment shaped beams was unexpected and highlights deficiencies in the current design procedure. In addition, anchorage methods for longitudinal reinforcement (Figure 5) leave steel bars exposed to corrosion and cannot be used if advanced composite reinforcement is to be used, an area of future development, discussed below.

3.8 The future design of fabric-formed concrete structures

The field of fabric formwork is by no means limited to beams. Shells, working efficiently in membrane action, offer great advantages, but their design and construction are more complex than bending elements and they are rarely used in commercial building systems. However, the construction of shell structures using fabric formwork is well established at CAST, and work is being undertaken by the authors to investigate the potential for large scale uses of fabric formed shell structures that will bring further material and cost savings to concrete construction. Polymer (CFRP) sheet, acting as reinforcement and permanent formwork, is currently being investigated at the University of Bath. The high tensile strength and durability of advanced composites also makes them a logical alternative to steel as longitudinal reinforcement, but introduces new design problems. As welded end plates cannot be used for the anchorage of longitudinal FRP reinforcement, current research is investigating the use of an innovative wedging anchorage method for FRP bars. See Figure 9. The concept has been proven in cube pull out tests [14] where order of magnitude increases in load and displacement capacity were seen, and verification by beam tests is now required. However, advanced composites have high working strains and are therefore inefficient when used in passively reinforced structures. Advanced composites are most effectively used in prestressed structures, where greater moment capacity can be obtained and the full tensile strength of the tendon utilised. Post tensioned fabric formed beams are an exciting prospect, and offer potential improvements in moment and shear capacity. By sewing ducts into the formwork, tendon positioning within the section can be ensured, and the use of unbonded advanced composite rope bypasses potential corrosion concerns.

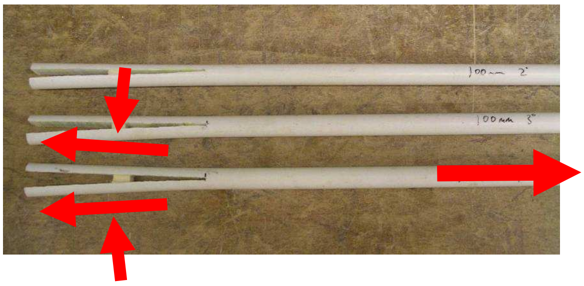

Figure 9: *Wedge anchorage system for FRP bars*

Figure 10: *Possible future fabric-formed structures*

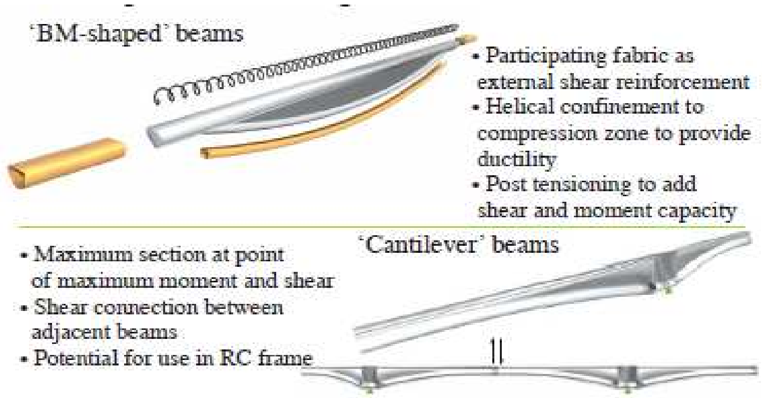

Figure 11: *Future innovations for fabric-formed structures*

4 Conclusions

Fabric formed concrete beams offer significant advantages for designers, including material reductions, ease of construction and aesthetic appeal. The forms are predictable and the development of robust methods for their design and optimisation is well underway. New materials, including advanced composites, prestressed reinforcement and fibre reinforced concrete offer additional advantages for fabric formed beams that will be investigated in future work.

5 Acknowledgements

The authors wish to gratefully acknowledge the financial contribution to this research which has been received from The Engineering and Physical Sciences Research Council of the UK, from Atkins Global and from the University of Bath. Grateful thanks are also due to all the technical staff in the Department of Architecture and Civil Engineering for their help in experimentation.

References

[1] Concrete Society 2004. Design guidance for strengthening concrete structures using fibre composite materials. Technical Report 55, Crowthorne. 102pp.

[2] Cluett, J. 2005. The strengthening of rectangular columns using FRP wrap. MEng dissertation, University of Bath.

[3] Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L. 2002. FRP strengthened concrete structures, Chichester, Wiley.

[4] Denton, S.R., Shave, J.D. and Porter, A.D. 2004. Shear strengthening of reinforced concrete structures using FRP composite. *Advanced polymer composites for structural applications in construction*. Woodhead, pp134-143.

[5] Wen, X. 2006. Size effect in shear behaviour of FRP-strengthened concrete beams. MPhil dissertation, University of Bath.

[6] Lamberton, B.A., 1989. Fabric forms for concrete. *Concrete International.* 11(12): 58-67.

[7] West, M., 2007. Construction. Winnipeg: Centre for Architectural Structures and Technology, University of Manitoba.

[8] Garbett, J., 2008. Bone growth analogy for optimising flexibly formed concrete beams. Thesis (MEng). University of Bath: Bath.

[9] Veenendaal, D., 2008. Evolutionary Optimization of Fabric Formed Structural Elements. Thesis (MS). Delft University of Technology: Delft.

[10] Bailiss, J., 2006. Fabric-formed concrete beams: Design and analysis. Thesis (MEng). University of Bath: Bath

[11] CAN/CSA S6:2006. Canadian Highway Bridge Code. CSA.

[12] Rozvany, G.I.N., 2008. A critical review of established methods of structural topology optimization. Struct Multidisc Optim. 37: 217-237

[13] Ibell, T.J., Darby, A.P., Bailiss, J.A., 2007. Fabric formed concrete beams. In: Darby, A.P., ed. ACIC 2007, April 2-4 2007, Bath: University of Bath.

[14] Darby, A.D., Ibell, T.J., Tallis, S., & Winkle, C., 2007. End Anchorage for Internal FRP reinforcement. In: Triantafillou, T.C., ed. FRPRCS-8, July 16-18, University of Patras